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THESIS

SOLAR SIMULATION LABORATORY
DESCRIPTION AND MANUAL

by

Kevin T. Mabie

June 1985

Thesis Advisor: A. E. Fuhs

Approved for public release; distribution unlimited

Prepared for: Department of the Navy
Commander Space and Naval Warfare
Systems Command
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Solar Simulation Laboratory
Description and Manual

by

Kevin Ted Mabie
Lieutenant, United States Navy
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requirements for the degree of

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This research project consisted of writing a manual for testing solar cells. It was written for students in the Space Operations and Space Engineering curricula. A location was selected at the Naval Postgraduate School and equipment was purchased for the construction. The manual begins with a introduction to solar cell theory. The individual components of the solar power laboratory are discussed in detail and their integration into a system is described. The system was designed for automated data acquisition. An IBM PC/XT is the central point of the system. Two computer programs written in IBM BASIC are included for the user with a complete discussion of each.

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I. INTRODUCTION

This thesis is a description of the construction and integration of components for a solar power laboratory at the Naval Postgraduate School in Monterey, California. Room 033B in Halligan Hall was selected to house the laboratory equipment. Funding was provided by the research sponsors at the Naval Postgraduate school and the Navy Electronic Systems Command. After funding was secured, the material needed to build the solar power laboratory was ordered. Building the laboratory consisted of integrating the different components into a usable, automated data acquisition system (all of which will be discussed in Chapters III and IV).

The laboratory was constructed for the benefit of students and instructors in the Space Systems Operations and Space Engineering curriculums.

The laboratory facilities allow for single cell tests at this time. There is ample space and equipment to expand into limited multiple cell testing. These tests encompass a wide range of possibilities including the following: I-V curves, and temperature, radiation and laser effects. Students will use existing facilities and equipment at the Postgraduate school for all tests.

The laboratory will be used for research and class oriented instruction, allowing students to become familiar with power systems utilizing photovoltaics.

Chapter II gives a brief history of the solar cell and also describes its operating principles, electrical considerations, radiation and laser effects. This chapter finishes with a discussion of current solar cell technology.

Chapter III describes the instrumentation and software used in the solar power laboratory. Hardware and software components allow the solar power laboratory to be a fully automated data acquisition solar cell test facility.

Chapter IV discusses the testing of solar cells using laboratory facilities. It will also discuss integrating the different components into a system to generate I-V curves using automated data acquisition.

Chapter V discusses error analysis. This analysis will include sources of errors, error correction and compensation.

Chapter VI presents conclusions.

II. INTRODUCTION TO SOLAR CELLS

The photovoltaic effect was discovered in 1839 by E. Becquerel and the first solid-state photovoltaic device was made in 1876 [Ref. 1]. The utilization of this effect to solar energy conversion gained significance only in the past 25 years.

Solar cells are devices in which sunlight releases electric charges so they can move freely in a semiconductor and ultimately flow through an electric load. This phenomenon of producing voltages and currents is known as the photovoltaic effect.

Photovoltaic solar energy conversion has provided the power for most of the spacecraft launched by all nations. In the field of aerospace, solar energy is a proven and suitable energy source, and photovoltaic conversion devices have proven themselves as the key to a lightweight and highly reliable power supply system.

The major utilization of solar cells is for space applications. Increasing satellite power requirements have advanced photovoltaic technology for the past 25 years. Terrestrial applications of solar cells has lagged behind and only in recent years is the development accelerating. The reason for the lack of solar cell terrestrial applications is the high cost of solar cell technology, and the opinion

that the world supply of hydrocarbon fuels,as an energy supply, was inexhaustible. With the cost of conventional fuels increasing and the cost of solar cells decreasing, as new frabrication techniques develop, the terrestrial application of solar cells becomes important. This thesis will concentrate on solar cells for space applications, although the theory of operation is the same for both.

Engineering of a solar cell power system must start with a thorough knowledge of the solar cell. The investigation must begin with a theory of operation. Various parameters must be tested, including: electrical quantities, efficiency, temperature and radiation(natural,nuclear) effects. With these parameters in mind, the engineer must also consider cost, weight and the type of solar cell needed for the application.

A. SOLAR SPECTRUM

In order to understand how we can use solar cells to obtain electrical energy from sunlight, we need to know about the nature of light and the units that are used to measure radiation.

Sunlight is measured in terms of power density. Power density is the amount of power crossing a given area expressed in terms of milliwatts per square centimeter

(mW/cm^2) or kilowatts per square meter (kW/m^2). Power density is also referred to as irradiance or intensity.

Air mass zero (AM0) is located outside the earth's atmosphere. AM0 is approximately 1.5×10^{11} m [Ref. 2] measured from the sun to the earth. This distance is also known as 1 astronomical unit. At AM0 a solar constant is established by high altitude balloon tests and direct measurement. The solar constant is defined [Ref. 3] as the rate at which energy is received upon a unit surface, perpendicular to the sun's direction, in free space at the earth's mean distance from the sun. Johnson [Ref. 4] gives a solar constant of 139.5 mW/cm^2. Thekaekara [Ref. 5] gives 135.3 +/- 2.1 mW/cm^2 and Neckel [Ref. 6] gives a value between 136.8 and 137.7 mW/cm^2. The spectral irradiance for AM0 is shown in Figure 2.1.

For representation of the complex and varying conditions of the atmosphere and its effects on the intensity and spectrum of energy, the optical air mass m is used. It is defined as the path length of radiation through the atmosphere considering the vertical path at sea level as unity. The air mass can be defined as $m=1/\cos(z)$ where z is the angle between a line vertical to the observer and a line through the observer and the sun [Ref. 7]. This formula only applies in the atmosphere. AMm where m=0 is used for notation only and is the condition in space. AM1 would occur

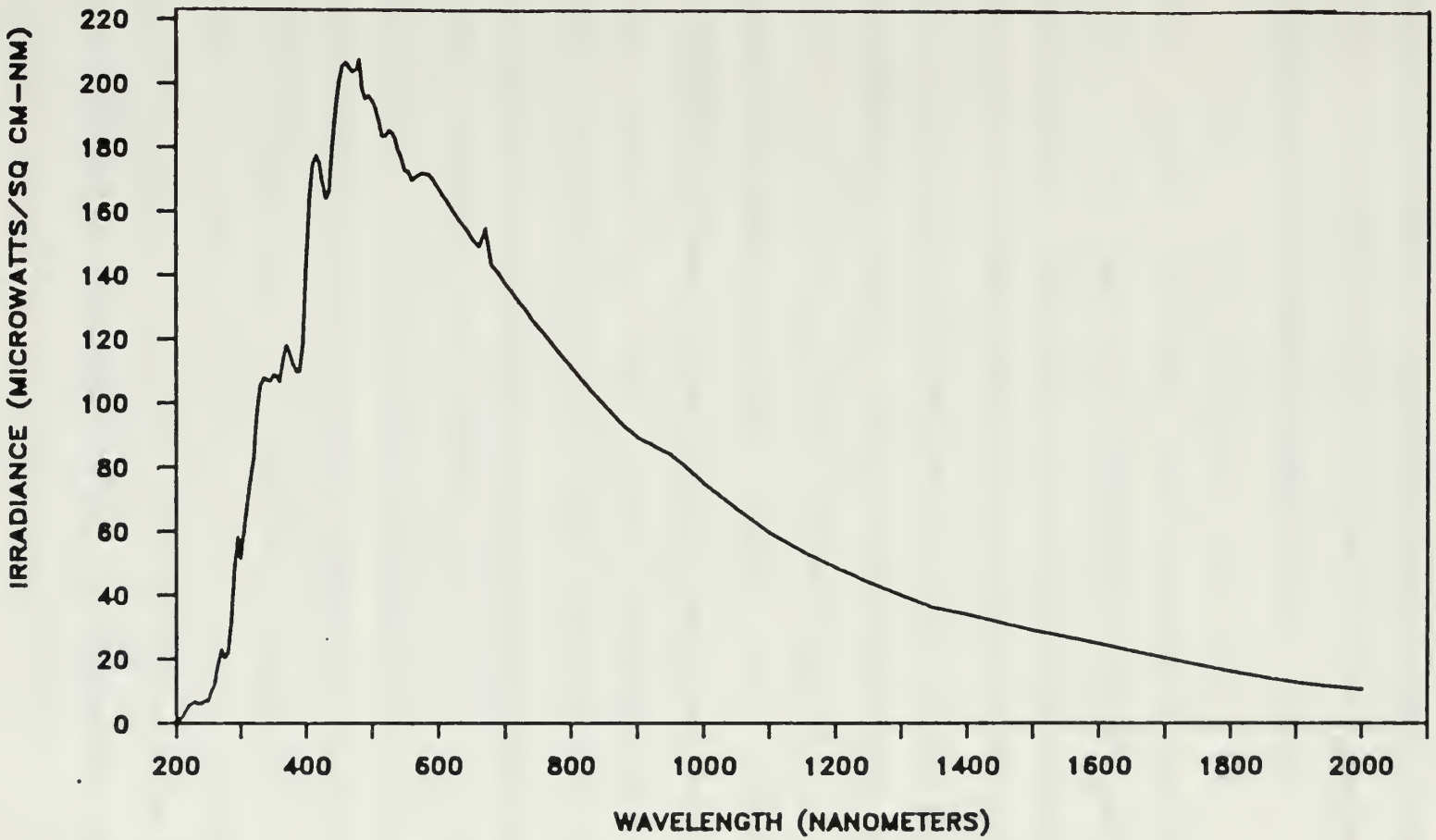

Figure 2.1 Air Mass Zero Solar Spectrum

when z=0° and AM2 occurs when z=60°. AM1 is approximately 0.7 X AM0.

In summary, AM0 would be measured as a distance from the sun and as a power density equal to 135.5 mW/cm^2. AM1 would equal 0.7 X 135.5. This gives a value for AM1 of 94.85 mW/cm^2.

B. SOLAR CELL THEORY OF OPERATION

Photovoltaic conversion is a process of converting radiant energy into electric charge separation. Most solar cells are composed of crystalline semiconductors that have solid state characteristics which promote separation of charge and a resultant flow of electric current in an external circuit [Ref. 8]. This external circuit is usually called the load. This load dissipates the power generated by the photovoltaic device.

In order to understand how a solar cell works, an introduction into the principles of semiconductor operation is needed. This explanation is confined to silicon solar cells.

After a silicon crystal has been grown, it can be used for solar cells. The crystal lattice of pure silicon has no free electrons, and, as a result, it is a poor conductor of electricity.

Silicon is altered and made useful for solar cells by adding small amounts of other elements. This process is called doping.

When phosphorus is added to silicon while the crystal is forming, there will be an excess of electrons which can move about in the crystal structure. These electrons are called n-type charge carriers. Silicon that is doped with phosphorus is called n-type silicon.

If boron is added to the silicon while the crystal is being formed, electrons will be removed from the silicon lattice. This absence of electrons creates voids in the crystal. These voids are called holes and act like positive charges. These holes can move easily from one place in the crystal structure to another. The holes move by the electrons filling them. Each hole will have a positive charge. Silicon doped with boron is called p-type or positive silicon [Ref. 9].

When p-type and n-type silicon are combined, a semiconductor junction is formed. This junction is formed near the front surface by diffusing n-type silicon into a p-type silicon to make a n/p junction. A p/n junction can also be formed by diffusing a p-type silicon into a n-type silicon [Ref. 10]. The p/n junction is located in a plane parallel to the surface exposed to solar radiation. Refer to figure 2.2 for a diagram of a p/n junction solar cell.

When a photon penetrates a solar cell it will force an electron out of its place in the crystal structure. This forms a hole-electron pair. When an electron moves back into the hole, the process is called recombination.

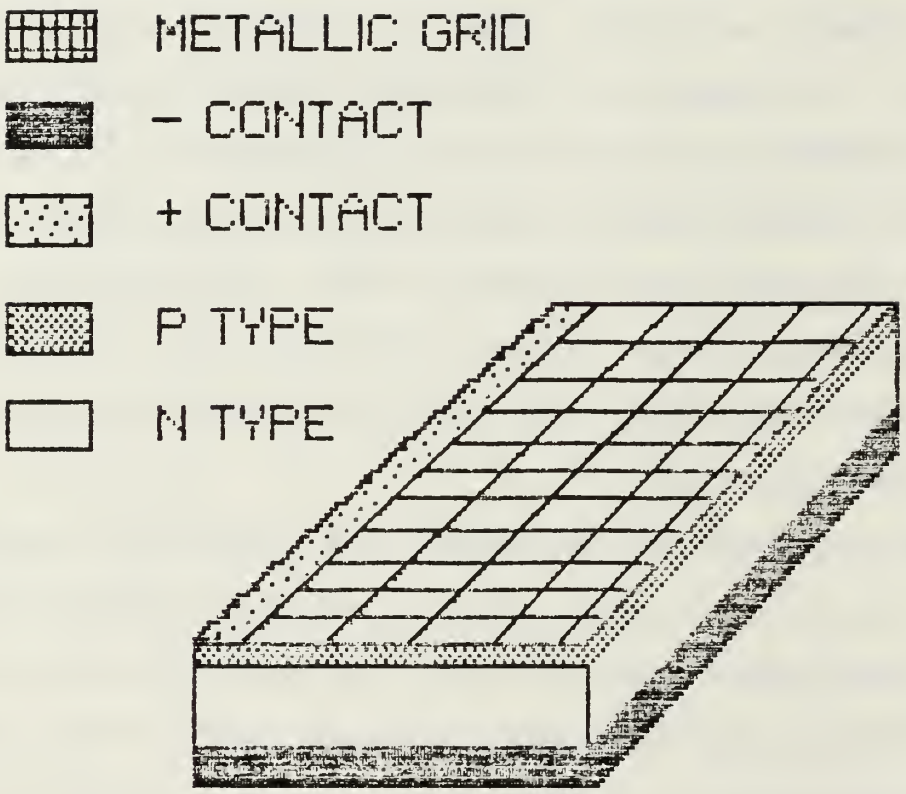

Figure 2.2 Typical p/n Junction Solar Cell

It takes 1.12 eV of energy, known as the band gap energy(E_g) of silicon, to separate an electron from the atom and create a electron-hole pair [Ref. 11]. The energy needed to create the electron-hole pair is supplied by sunlight or photons. Each photon has energy $h\nu$ where h is Planck's constant and ν is the frequency of the light wave. A semiconductor can absorb photons having $h\nu > E_g$. Each photon that is greater then E_g can generate only one electron-hole pair. Excess energy is dissipated as heat.

Semiconductors are grouped into two types, direct-gap and indirect-gap. Direct-gap semiconductors are GaAs, InP, CdS and Cu_2S. Indirect-gap are Si, Ge and GaP. Indirect-gap semiconductors are much thicker than direct-gap; 100μm as compared to 1-10μm. Indirect-gap semiconductors cannot absorb photons with $h\nu > E_g$ until the sample is at least 100μm thick.[Ref. 12]

An internal electric field is formed in a solar cell because the excess electrons in the resulting n-region will move over into the existing p-region, and holes from the p-region will move to the n-region. The resulting charge separation will prevent further net charge movement.

The n/p junction will accelerate electrons toward the front surface and holes toward the rear surface. This electric field only exists near the n/p junction and is called the space charge or depletion region. Any electron which now enters this region will be discharged into the

n-region of the cell where it will be a majority carrier. The majority carrier has a high probability of reaching the front electrical contact. Holes produced in the n-region entering the depletion region will be accelerated towards the rear contact.[Ref. 13]

The following is a list of terms that are useful in the discussion of solar cells.

Mobility - How rapidly a charge carrier will move on application of an electric field, or the average drift velocity per unit electric field.

Lifetime - The average time between electron-hole pair creation and recombination.

Mean Free Path - The average distance traveled between collisions for a carrier moving through a material.

Diffusion Length - The average distance a carrier diffuses before recombination.

Recombination Rate - The rate at which excess electrons and holes recombine and annihilate each other in pairs.

In summary, to obtain useful power from photon interactions in a solar cell, three processes are required.

1) The photon has to be absorbed and result in a electron being excited to a higher energy level.

2) The electron-hole charge carriers created by the absorption must be separated and moved to a front or back contact to be collected.

3) The charge carriers must be removed to a useful load before they recombine with each other and lose their added potential energy.

C. SOLAR CELL ELECTRICAL CONSIDERATIONS

The electrical characteristics of a solar cell can be understood from Figure 2.3. This simplified equivalent

circuit consists of I_{sc}, the total minority carrier current across the junction (in "reverse" direction). I_{sc} is also referred to as the short-circuit current. R_s is the resistance of the very thin p-layer to the flow of current. R_s can be neglected for normal operations. R_L is the resistance of the load. R_j is the junction resistance.

In the absence of an electrical connection between the p-type and n-type materials, the net current is zero. Since the net current is zero, a potential V developes across the junction which pushes an equal and opposite current in the "forward" direction. This forward current is identical to that which would be obtained by placing the bias voltage V across the p/n junction in a "forward" direction. Light causes a current, I_L, to flow in the load given by

$$I_L = I_{sc} - I_j \qquad (1)$$

I_j, the nonlinear junction current, is given by

$$I_j = I_o\left[e^{qV/kT} - 1\right] \qquad (2)$$

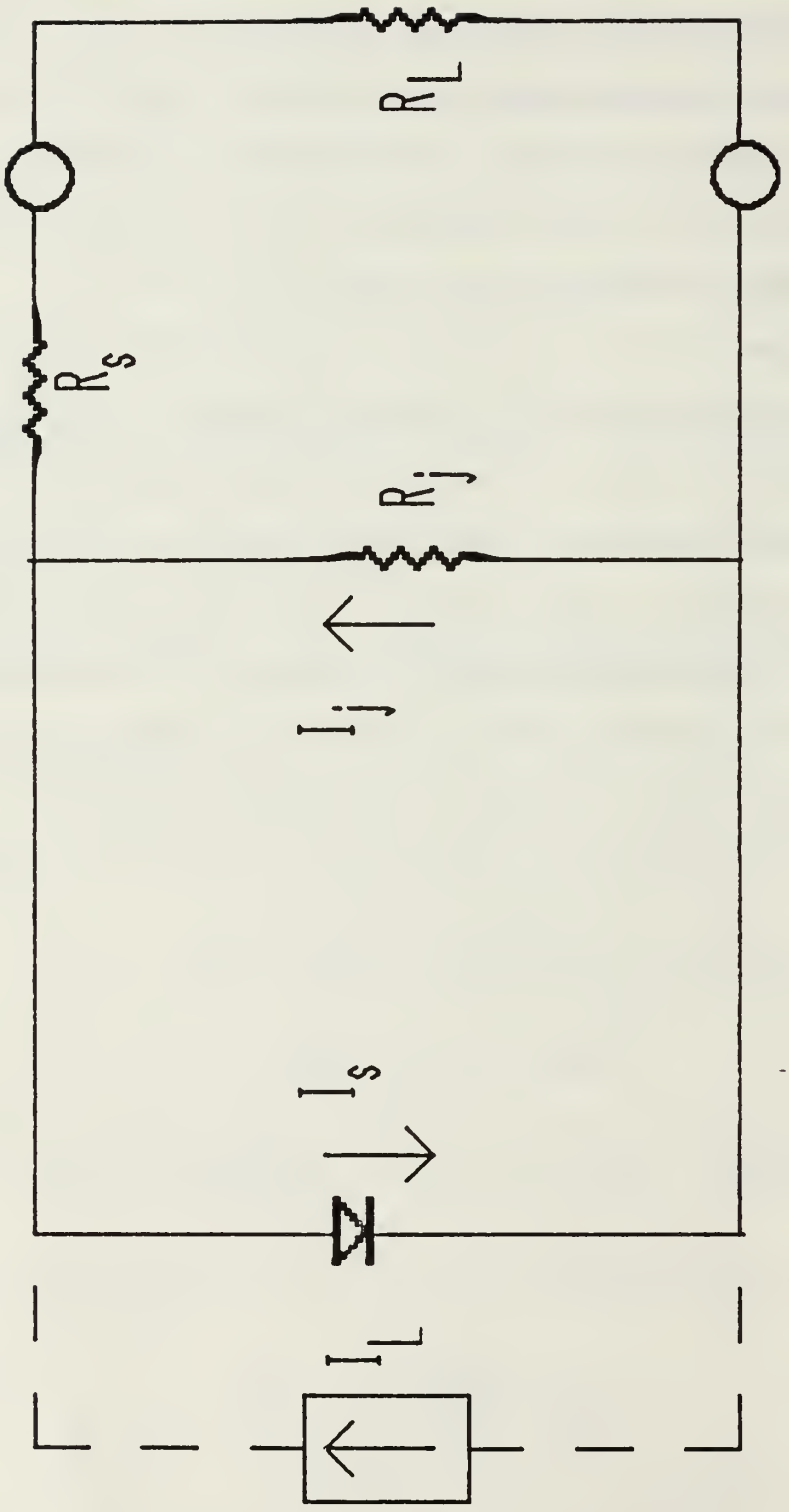

Figure 2.3 Simplified Circuit of Solar Cell

where

I_j = Junction Current

I_o = dark or reverse saturation current

V = Voltage developed across the junction

k = Boltzmann Constant

T = Absolute temperature

Combining equations 1 and 2 gives

$$I_L = I_{sc} - I_o\left[e^{qV/kT} - 1\right] \qquad (3)$$

The maximum voltage, V_{oc}, occurs when I_L=0 from equation 3. Solving for V when I_L=0 gives

$$V_{oc} = \frac{kT}{q}Ln\left[\frac{I_{sc}}{I_o} + 1\right] \qquad (4)$$

where

V_{oc} = Open circuit voltage.

The maximum power will be generated when $R_L = R_j$. This is when impedances are matched. The nonlinear junction resistance, R_j, can be obtained from equation 2.

$$R_j = \frac{V_j}{I_j} = \frac{kT}{qI_o}e^{-qV/kT} \qquad (5)$$

Remembering that $R_j = R_L$ for maximum power:

$$R_L = R_j = \frac{kT}{qI_o}e^{-qV_{mp}/kT} \qquad (6)$$

where

V_{mp} = Maximum power voltage.

For maximum power the current passing through the load resistor is given by

$$I_{mp} = \frac{V_{mp}}{R_{L,mp}} \qquad (7)$$

where

I_{mp} = Maximum power current

$R_{L,mp}$ = Resistance of the load at maximum power

From the product of I_{mp} and V_{mp} the maximum power can be obtained

$$P_{max} = \left[\frac{\lambda V_{mp}}{1 + \lambda V_{mp}}\right] \left[\frac{I_o}{I_s} + 1\right] I_{sc} \times V_{mp} \qquad (8)$$

where

P_{max} = Maximum power obtained

λ = q/kT

Figure 2.4 shows the behavior of an illuminated solar cell current vs. voltage as R_L varies from Ø to infinity. This figure is called a I-V curve and is the primary engineering tool that characterizes a solar cell.

For a more complete discussion of the equations governing solar cell operation refer to references 14,15,16.

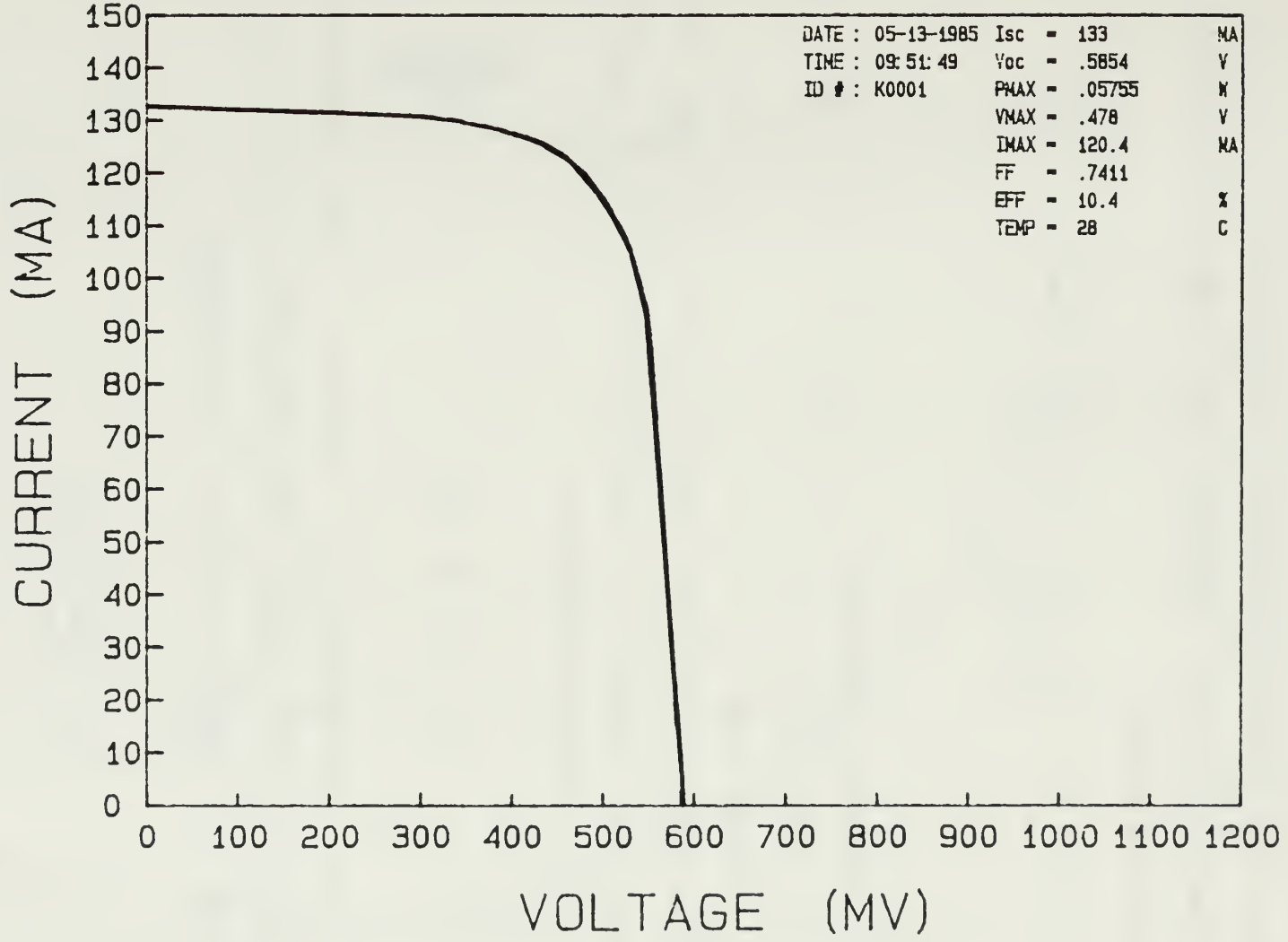

Figure 2.4 Typical I-V Curve

D. SOLAR CELL EFFICIENCY CONSIDERATIONS

Solar cell energy conversion efficiency is the ratio of the power output to the power input. Cell efficiency is given by the equation

$$\eta = \frac{P_o}{P_i} \qquad (9)$$

Where

η = Conversion efficiency

P_o = Power output

P_i = Power input

Referring to Figure 2.5 a specific pair of voltages and currents will maximize P_o. These points are called I_{mp} and V_{mp}. P_o is given by the equation

$$P_o = I_{mp} \; X \; V_{mp} \qquad (10)$$

The fill factor(FF) is a measure of the effective utilization of the power producing capability of a solar cell. The fill factor is given by the equation:

$$FF = \frac{I_{mp} \; X \; V_{mp}}{V_{oc} \; X \; I_{sc}} \qquad (11)$$

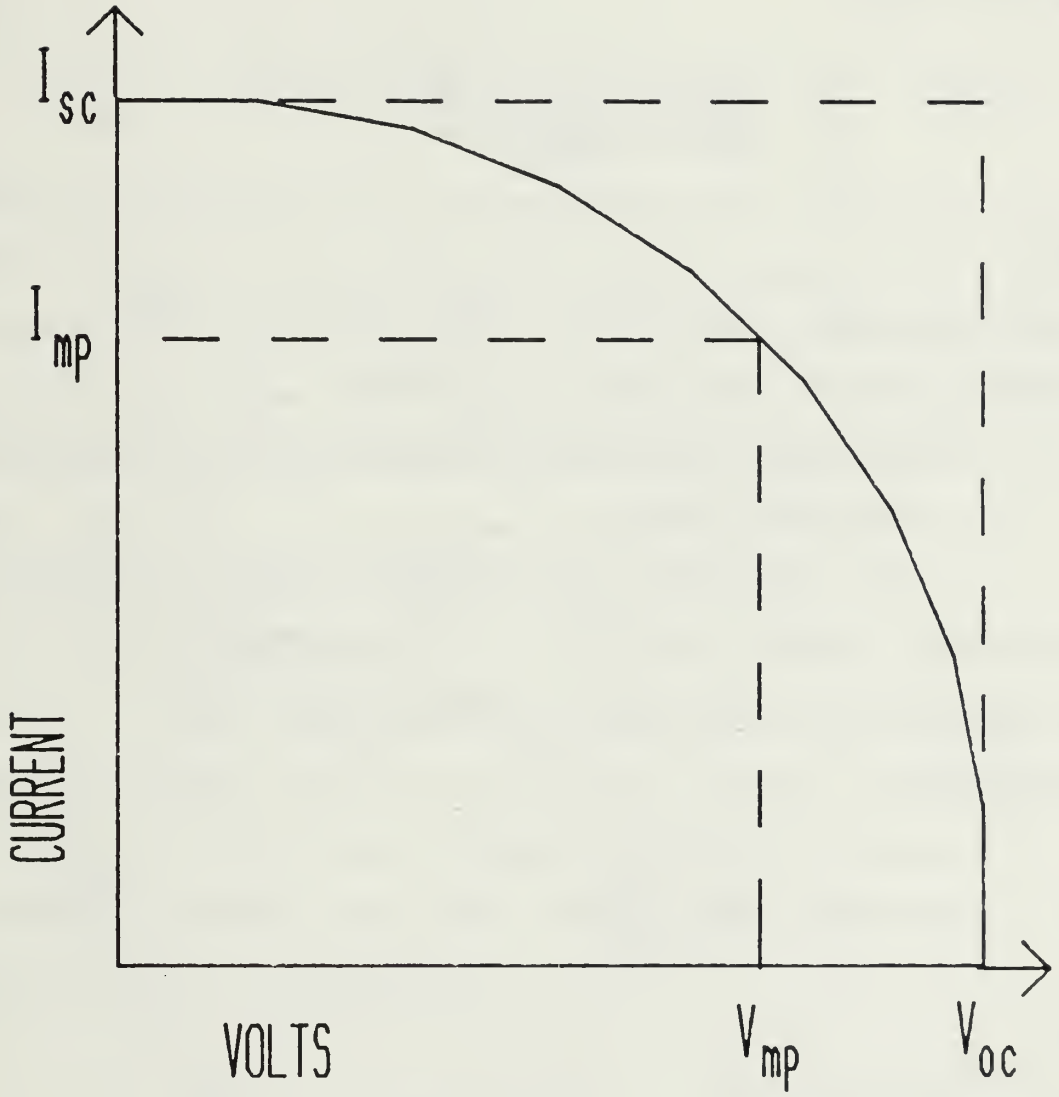

Figure 2.5 I-V Curve Showing Maximum Power Points and Fill Factor

An inspection of Figure 2.5 shows that the fill factor is the ratio of the area of the largest rectangle that can fit under the I-V curve to the product V_{oc} X I_{sc}.

Rearranging equation 10 and 11 and substituting into equation 9 gives

$$\eta = \frac{V_{oc} \text{ X } I_{sc} \text{ X } FF}{ISP \text{ X } AREA} \qquad (12)$$

where

ISP = Incident solar power (135.5 mW/cm^2 for AM0)

AREA = Area of the solar cell tested in cm^2

1. Factors Affecting Solar Cell Conversion Efficiency

a. Band Gap Energy

In discussing the band gap energy it is useful to define the voltage factor(VF). It is a measure of how effectively the cell potential is being used. VF is given by the equation

$$VF = \frac{V_{oc}}{E_g} \qquad (13)$$

where

VF = Voltage factor

E_g = Band Gap Energy

Rearranging equation 13

$$V_{oc} = VF \text{ X } E_g \qquad (14)$$

This shows that V_{oc} is directly proportional to increasing E_g. Substituting equation 14 and 11 into equation 10 gives

$$P_o = FF \text{ X } VF \text{ X } I_{sc} \text{ X } E_g \qquad (15)$$

Equation 15 shows how E_g affects the power output and hence the conversion efficiency. Since I_{sc} decreases with increasing E_g, the solar cell efficiency will peak at a certain E_g. Figure 2.6 shows the maximum theoretical efficiency as a function of E_g for different solar cell materials. This maximum efficiency can be changed in concentrator systems and in systems involving composite materials.[Ref. 17]

b. Temperature

The temperature of a solar cell influences the amount of power that it will deliver; hence, the efficiency decreases with increasing temperature. V_{oc} is the major contributing factor to this temperature dependence. The relationship is expressed as

$$\frac{dV_{oc}}{dT} = -0.00288 \text{ VOLT} / {}^{o}C \qquad (16)$$

This value is for silicon solar cells. It is generally rounded off to -2 mV/°C. The output voltage can be calculated from the following equation:

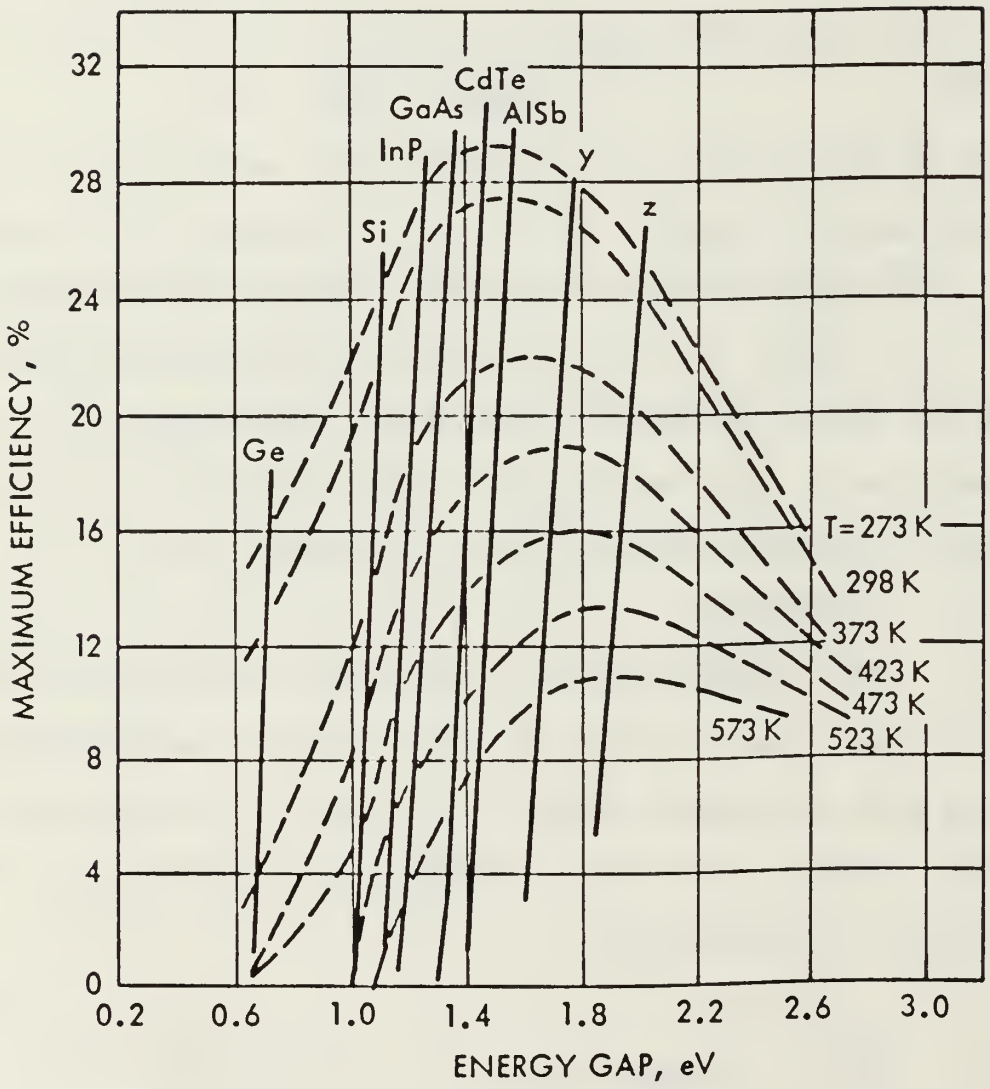

Figure 2.6 Maximum Efficiency as a Function of Band Gap Energy (Reproduced from JPL Publication 82-69, Solar Cell Radiation Handbook)

$$V_{out} = V_{ref}\left[1 - 0.002(T - 20^{o})\right] \qquad (17)$$

where

V_{out} = Output of the solar cell in volts

V_{ref} = Output of the solar cell in volts at 20 °C

T = Temperature in degrees celsius

I_{sc} increases with increasing temperature by +28 uA/°C. This increase in I_{sc} is not enough to effect P_{o}.

c. Radiation Effects

In the study of radiation degradation effects, two sources are of main concern, natural space radiation and nuclear radiation. The particles that cause the damage are electrons, protons, neutrons and ions.

High energy particles will displace atoms in a solar cell crystal. These displaced atoms act as additional recombination centers for electron-hole pairs. The net effect is that fewer electron-hole pairs reach the junction to produce current.[Ref. 18]

Particles below a given threshold will not produce damage to the solar cell crystal. For protons the threshold is 100 eV and for electrons it is 145 keV for n-type silicon cells and and 200 keV for p-type cells. [Ref. 19]

Radiation damage is greater for longer wavelengths such as in the infrared region. This is because longer wavelengths penetrate the solar cell to a greater depth. Therefore, it becomes very important that the light

source match the AM0 spectrum when testing solar cells for radiation damage.

Radiation damage from natural space environment must be contended with, and this radiation degradation must be engineered into a solar cell power system. The spacecraft engineer must design towards spacecraft end-of-life(EOL) requirements. If a 1 kW power system is needed and the 7 year degradation is 25%, then the satellite will be launched with a 1.25 kW system.

Radiation damage is reduced by applying glass covers on the solar cells. This coverglass will shield the solar cell from lower energy particles.

Degradation for a typical silicon solar cell after seven years is approximately 20 percent with one-half of the damage occurring in the first two years. [Ref. 20]

2. Improvement of Solar Cell Efficiency

To achieve high efficiency, it is desirable to have a large short-circuit current, high open-circuit voltage and a large fill factor. The short-circuit current is higher if the solar cell is made from materials with a small energy gap.

The highest efficiencies are from solar cells made from materials with E_g between 1.2 and 1.6 eV.

Various techniques have been used to improve silicon solar cell efficiency. These techniques include:

1) Shallow junction solar cells (Violet cell)

2) Back surface field (BSF) or (P+) solar cells

3) Textured surface solar cells

4) Vertical junction solar cells (VJ)

5) Back surface reflector (BSR) solar cells

For a more complete discussion of these cell refer to reference 21.

E. NEW SOLAR CELL TECHNOLOGY

Silicon solar cell technology is over 25 years old. Research and development is being conducted on more promising solar cells. These new solar cells yield higher efficiencies at higher operating temperatures and are more radiation resistant.

1. Gallium Arsenide

The use of GaAs as the semiconductor material in solar cells is at present the best way to achieve high conversion efficiency, high temperature tolerance and better radiation resistance.

Conversions efficiencies of 16-19 percent for AM0 have been reported [Ref. 22].

Some problems exist with the GaAs cell. GaAs is much more expensive than silicon to produce, and it weighs more than silicon for the same conversion efficiency. These two reasons are why GaAs has not been used extensively.

Typical GaAs cells can withstand more radiation damage than silicon and have better annealing properties. GaAs has much better operating characteristics at high temperatures. [Ref. 23]

Different types of Gallium Arsenide solar cells have been developed. The GaAs thin cell (3 mills thick compared to 10 mills for typical GaAs cells) solves the weight problem. Also developed is the AlGaAs/GaAs solar cell. This cell was developed to slow down the surface recombination velocity of GaAs cells [Ref. 24].

2. Solar Cell Concentrators

Photovoltaic energy conversion utilizing sunlight concentration is a new and very promising technology.

The main reasons for using concentrator systems instead of conventional solar arrays are the cost incentive and spacecraft survivability. Cost reduction arises from the replacement of more costly solar cell material by less costly concentrators elements, such as optical components.

Many different concentrator designs have been constructed. The most widely accepted design is the Cassegrainian concentrator. In a Cassegrainian type system, sunlight is reflected by a spherical or parabolic concave primary mirror. A smaller convex mirror intercepts the light and directs it towards the center of the primary mirror

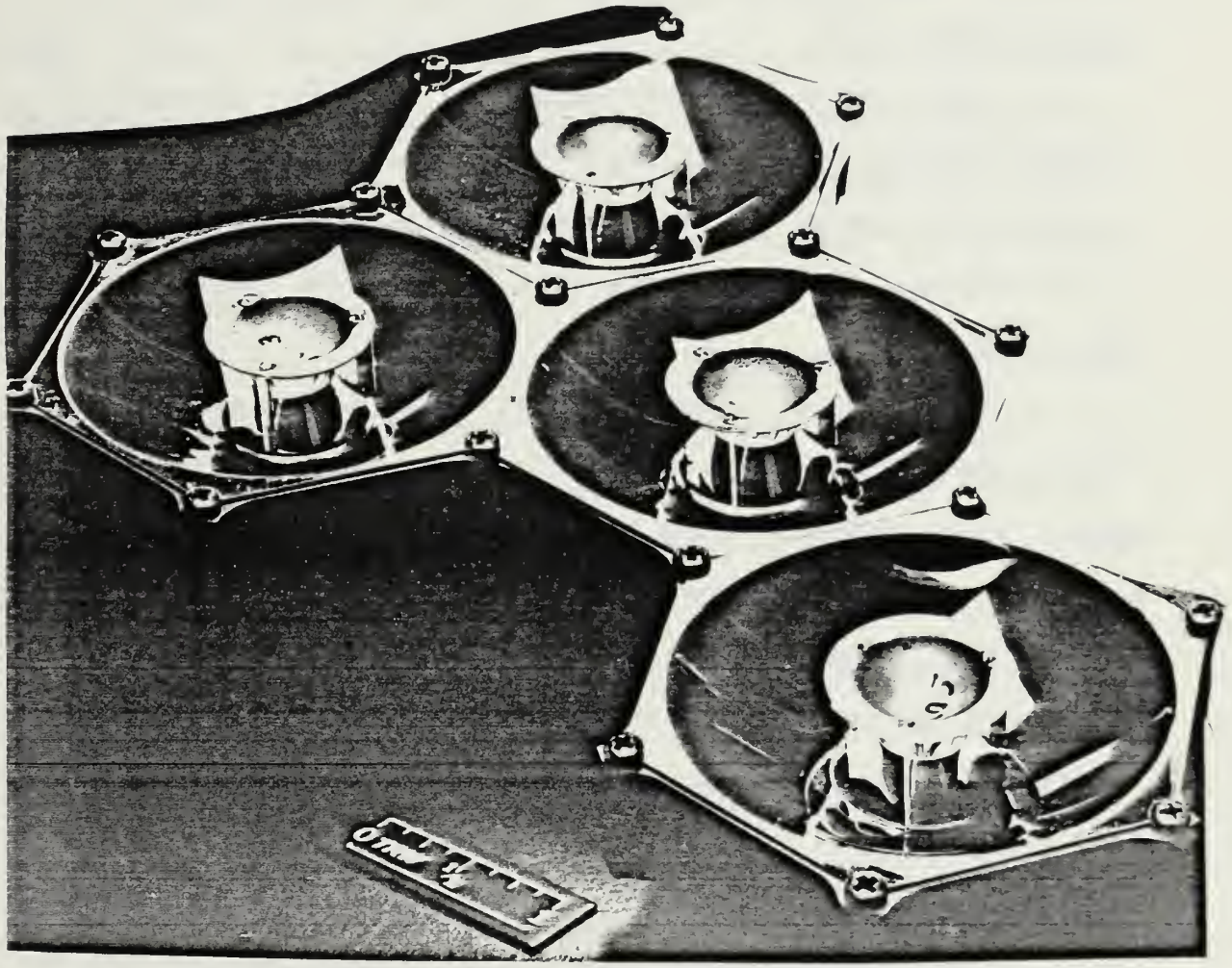

Figure 2.7 Typical Cassegrainian Concentrator
(Courtesy of TRW Systems INC.)

where one or more solar cells are positioned. Figure 2.7 show a typical Cassegrainian concentrator.

Although the Cassegrainian concentrator has received the most interest, other concentrator designs are being studied. These include: Fresnel lens and venetian blind systems [Ref. 25].

GaAs is the dominate solar cell used in concentrator systems because of its superior performance characteristics at the high operating temperatures of a solar concentrator. It is normally 5x5 mm in size with a 4x4 mm active area. [Ref. 26]

Concentrator systems will also increase radiation resistance and are less vulnerable to laser attack. In a solar concentrator, only rays within an angle θ from the axis of the system can be focused on the solar cell. θ is called the acceptance angle. Rays coming from outside this acceptance angle will not reach the solar cell. The defense department is looking very strongly at concentrators for the next generation of satellites because of their hardened characteristics.

The concentration ratio is the area of the lens or reflector divided by the area of the solar cell. If the ratio was 100X, the cell would be illuminated by light 100 times more intense than normal sunlight. Photovoltaic concentrators can achieve a concentration ratio from 10X to 1000X. Optimum concentration ratios' are 100X-500X.[Ref. 27]

III. INSTRUMENTATION AND EQUIPMENT FOR THE SOLAR POWER LABORATORY

A. KRATOS LIGHT SOURCE

The light source is a KRATOS LH152 Xenon lamp rated at 2500 watts. The Xenon lamp is designed to simulate the AM0 spectral response(135.5 mW/cm^2 over a one square foot area).

The Xenon lamp is ozone free and requires ventilation and cooling with two external blowers arranged in a push-pull configuration.

Spectral filtering is done with the condenser system, optical and water filters. The condenser system uses UV grade quartz optics. The spectrum filtering is done with three quartz filters(AM0, AM1, AM2) and water filtering. The water is used to filter the infrared from the Xenon spectrum. The water is also used to cool the condensing system.

The power supply is a 230 volt 3-phase, 54 Amp system.

Refer to reference 28 for a complete discussion of the operating characteristics of the Kratos light source.

B. TEMPERATURE CONTROL SYSTEM

Temperature control for the testing of solar cells is accomplished with water. The water is circulated through the solar cell test block to maintain a constant temperature.

A Model 2067 CH/P temperature control bath from Forma Scientific is used to circulate the water through the test block.

The system has temperature selectivity in 0.1°C increments and an operating range of -20°C to +70°C with a +/- 0.02°C sensitivity. A liquid crystal display(L.C.D.) provides direct readout of actual bath temperature. The bath has two valves for external circulation of water to the test block.

The test block temperature lags the water bath temperature by several degrees and requires several minutes of circulation to stabilize the test block temperature.

Refer to reference 29 for a complete description of the Model 2067 CH/P temperature control bath.

C. ISAAC 2000 ANALOG/DIGITAL CONVERTER

Data acquisition is accomplished using an ISAAC 2000 A/D CONVERTER with a C-100 four channel high speed, 12-bit A/D conversion module installed.

The ISAAC 2000 has the following components installed: 16-bit Motorola 68000 microprocessor used as a system controller, 128K bytes of RAM, 32K bytes of ROM(ISAAC command language(ICL)), C-100 12-bit A/D CONVERTER, two serial ports, and one IEEE-488(GPIB) bus port. Eight slots are available for expansion.

The C-100 12-bit, four channel module samples at 200

kilohertz for a single channel and multiple channels may be sampled at a fraction of the total(for example: 4 channels at 50 kilohertz). The C-100 has the following input ranges for each channel: +/- 5mV, +/- 10mV, 0-10mV, +/- 50mV, +/- 100mV, 0-100mV, +/- .5V, +/- 1V, 0-1V, +/- 5V, +/- 10V, 0-10V.

1. Software For The ISAAC 2000

The ISAAC 2000 is controlled by an IBM PC/XT using Labsoft II software(Labsoft II is supplied by the ISAAC 2000 manufacturer). Labsoft II is accessed via IBM basic.

Additional commands in ICL are located in the ISAAC 2000 ROM. The commands are given to the ISAAC 2000 via Labsoft II. An example of a command would be:

FASC (Fast Analog Scan, for the C-100 board)

Example: FASC 32,0,2,3,20,1

Programming examples are given in Chapter IV. The IBM PC/XT is connected to the ISAAC 2000 by a serial port using RS232 protocol. Refer to reference 30 for a complete discussion of the ISAAC 2000.

D. KEPCO BIPOLAR POWER SUPPLY

The Kepco bipolar power supply is connected to the solar cell test block. The Kepco will produce a variable load so I-V curves can be produced.

The Kepco is connected to the IBM PC/XT via a IEEE 488 bus. The Kepco is given commands to increment the load resistance for the solar cell.

At the writing of this thesis, the Kepco has not been delivered.

E. SOLAR CELL TEST BLOCK

A solar cell test block was provided by Spectrolab(a division of Hughes Aircraft Co.). This test block is used to mount the solar cell under the light source for testing. The test block lays flat on a table under the Kratos light source. It is connected to a vacuum pump to hold down the solar cell so a good electrical connection can be made on the back contact.

The test block has water ports for cooling and is connected to the temperature control bath via a rubber circulation hose. The test block is connected to the variable load and the ISAAC 2000 via electrical leads. Thermocouple wire is connected to the test block for temperature measurement. The thermocouple is connected to the ISAAC 2000 for voltage measurement.

F. IBM PC/XT

Using NAVELEX funding, the IBM PC/XT used for the solar power laboratory has been expanded to include the following equipment:

1) 640K bytes RAM

2) 1 Asynchronous communication adapter

3) 2 RS232 serial ports

4) 1 IEEE-488 board and port

5) IBM color/graphics board

6) AMDAK color 710 monitor

7) 8087 INTELL coprocessor

The IBM PC/XT came standard with the following equipment:

1) 1 dual sided diskette drive

2) 1 10M byte fixed disk drive

3) 256K bytes RAM

The IBM PC/XT is used to control the ISAAC 2000 A/D CONVERTER. It is connected to a HP 7475A plotter and an EPSON FX-100 dot matrix printer. The printer and plotter are used to draw the I-V curves.

Using NAVELEX funding additional software was purchased to run on the IBM PC/XT. This software includes:

1) SYMPHONY

2) NWA STATPAK

3) ENERGRAPHICS

4) CHART MASTER

5) WORDSTAR 2000+

6) MATHEMATICAL PACKAGES

IV. TESTING SOLAR CELLS

A. INTEGRATING INSTRUMENTATION SYSTEMS FOR SOLAR CELL TESTS

To test solar cells, all of the components discussed in Chapter III must be integrated into a single system. The system will include the following: IBM PC/XT, ISAAC 2000, HP 7475A plotter, KRATOS light source, temperature control system and the solar cell test block.

1. IBM PC/XT, HP7475A and ISAAC 2000

The IBM PC/XT and the ISAAC 2000 were the first components integrated into the system. The IBM PC/XT was flawless in its operation, and no difficulties were encountered in its programming.

The ISAAC 2000 has experienced many problems since acquiring it. The ISAAC 2000 was sent back to Cyborg Corp. three times over a five month period for repairs. The solar lab is presently using a loaner from Cyborg Corp.

The IBM PC/XT is connected to the ISAAC 2000 by a RS232 connection. All programs were written in advanced basic ("BASICA"). BASICA was used because Cyborg Corp. supplied a program called "ISAACOMM.BAS" that must be used with the ISAAC 2000. ISAACOMM.BAS loads a machine language interface handler (ISAACOMM.BIN). The handler includes a series of specific calls that write ASCII strings to the ISAAC 2000 and reads the numbers and strings that the ISAAC 2000

returns. This interface handler can be used for general purpose interface bus(GPIB) or RS-232 configuration. Refer to reference 31 for a more detailed explanation of ISAACOMM.BAS and interface configuration.

a. Solar Cell Testing Program

Appendix A contains "SOLAR.BAS". SOLAR.BAS was written in BASICA and includes ISAACOMM.BAS from line 500 to line 690. ISAACOMM.BIN is loaded at line 520.

The main program starts with line 900 and ends at line 1610. The plotting subroutine starts at line 9000.

Variables are set to zero at line 900 and line 910. The screen is set to width 40 with a blue background and yellow foreground in line 1000 and line 1010.

Line 1030 through 1050 are strings that will be sent to the ISAAC 2000. These strings determine which channel will be sampled at what rate and how many samples will be taken. For example:

FASC 32,0,0,1,5,1

where

32= device number

0 = channel low to begin scan

0 = channel high to end scan

1 = number of samples

5 = rate at which scans are taken (uSec)

1 = gain (must be set equal to one)

Line 1060 to 1090 request user input. The user inputs the number of samples to be taken. This number is the number of samples plotted and not the number of samples taken by the ISAAC 2000. Line 1070 requests a cell ID#. This ID# can be anything from a number to the users name. Line 1080 to 1090 requests the cell size in height and width. The cell size is used to calculate the efficiency.

Lines 1110 to 1350 contains the main sampling loop. The inner loops sample the voltage, current and temperature. The voltage and current are sampled ten times and then block averaged to obtain 1 value. This averaging is done to reduce noise. The current is divided by .1 because the voltage is dropped across a .1 ohm resistor to obtain the current. Both the voltage and current are stored in arrays at line 1200 and line 1300.

When a command is sent to the ISAAC 2000 to take a sample and then return that sample to the IBM PC/XT, it is stored in the variable RAWVAL%. RAWVAL% contains the digitized value of the analog voltage. This digitized value is actually the quantization level within which the analog voltage occurs. This value can be converted to an analog value by the following method:

Analog Value = RAWVAL%*(Quantization Interval)-Input Range/2

where

Analog Value = Value obtained after calculation

RAWVAL% = Quantization level

Quantization Interval = Input range/ 2^n

(width of each level)

Input Range = Analog voltage input minimum to maximum value

The above calculation is done at line 1170 where the analog voltage input range is set to +/- 5 volts. The same calculation is done at line 1260 and line 1340 where the input range is +/- 100 mV.

The sampled values are converted and continuously displayed on the color monitor at line 1190,1290 and line 1345.

After N samples are taken, the program calculates V_{oc}, I_{sc}, P_{max}, V_{max}, I_{max} and the Efficiency. These calculations are done from line 1370 to line 1540.

V_{oc} and I_{sc} are found by setting V_{oc} and I_{sc} equal to the first value in the arrays X and Y. The values are then run through a loop at line 1380 and line 1420. These loops find the highest value in the arrays. The highest values found are equal to V_{oc} and I_{sc}.

P_{max} is calculated in much the same way as V_{oc} and I_{sc}. P_{max} is found by multiplying I_{mp} X V_{mp}. A loop is set up from line 1480 to line 1520. This loop finds P_{max} by

multiplying each voltage, current pair until a maximum value is found. This maximum value is P_{max} and the voltage, current pair that produced P_{max} is V_{max} and I_{max}.

The fill factor and efficiency are calculated in line 1530 and line 1540.

Lines 1550 to 1600 reset the screen color and requests user input. The user has the option of plotting the data, quitting or returning to the start of the program for another run.

The solar cell temperature is sampled at line 1310. This value is then converted at line 1340 and displayed by line 1345. The temperature is summed and divided by the number of samples taken. The final temperature that is printed on the plot is the average temperature during the time interval required for N samples.

Commands for the Kepco bipolar power supply to increment the resistance in the load can be inserted above line 1130. The Kepco will be connected to the IBM PC/XT by a GPIB.

(1) Plotting Subroutine. The plotting subroutine starts at line 9000. This subroutine is written for a HP7475A plotter. This subroutine will make a graph size of 5.5 by 8.5 inches including labels and titles. The subroutine scales the X axis form 0 to 1200 mV and the Y axis from 0 to 150 mA.

The subroutine will plot any number of points in the arrays X and Y. The HP7475A can only plot integers, so all values must be scaled to greater than one before plotting.

The subroutine will print the solar cell parameters obtained and already discussed. These include: V_{oc}, I_{sc}, P_{max}, V_{max}, I_{max}, fill factor, efficiency and temperature. The subroutine will also print the date, time and cell ID# on the plot.

Figure 2.4 is an example of the plot produced from this program.

Appendix B contains "SOLAR2.BAS". This program is exactly like SOLAR.BAS except for the plotting subroutine. This subroutine will autoscale the X axis and Y axis depending on what value of V_{oc} and I_{sc} are found in the main program. The solar cell parameters are plotted in the lower left corner vice the upper right. Figure 4.1 is an example of output from SOLAR2.BAS.

2. Temperature Control and Measurement

Temperature control is done with the Forma Scientific Model 2067 CH/P temperature control bath. The water is circulated through the solar cell test block with plastic hoses. The water bath must be running for several minutes to stabilize the temperature of the solar cell test block.

The temperature is measured with thermocouple wire connected to the solar cell test block and a thermocouple to

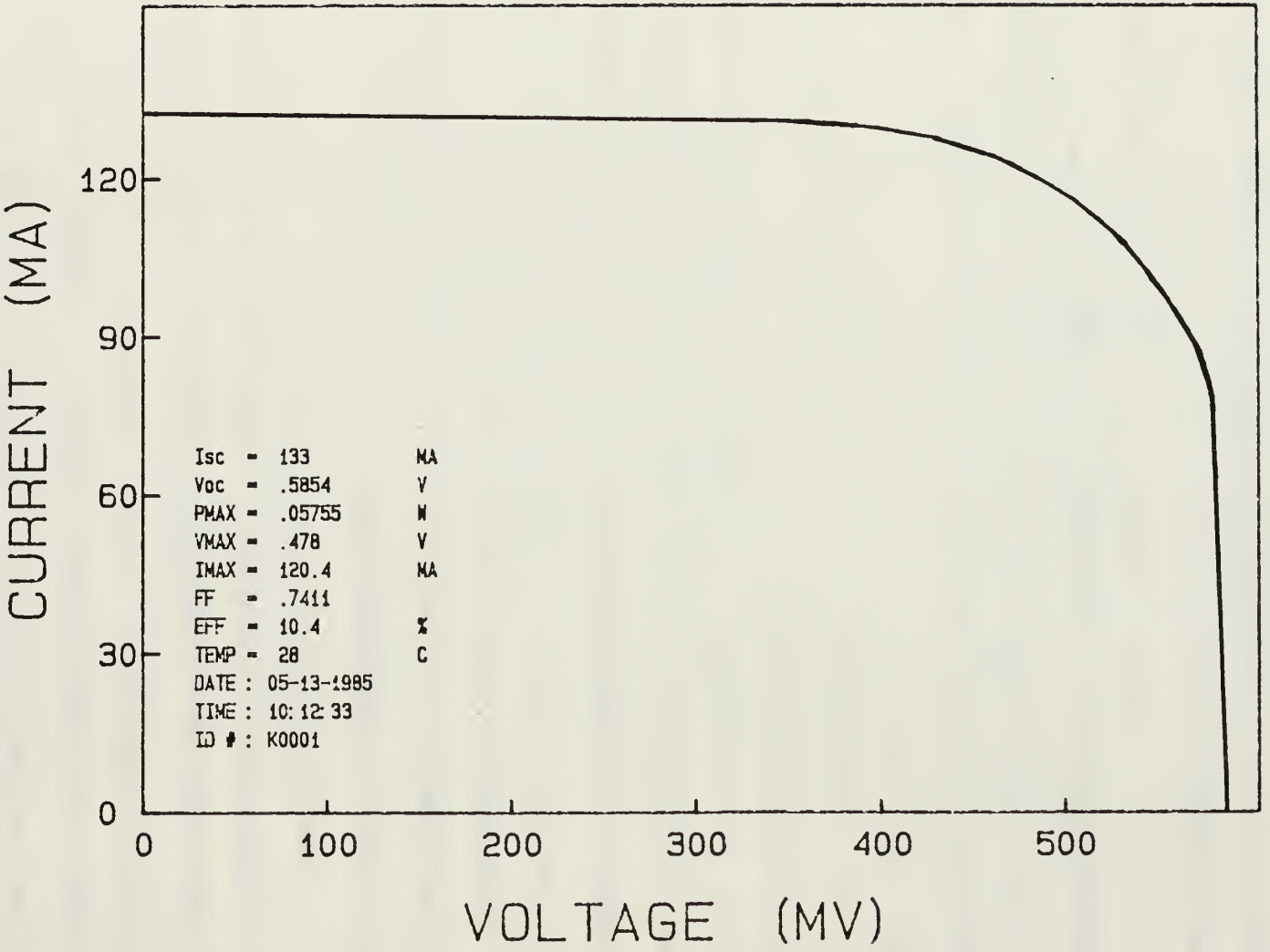

Figure 4.1 I-V Curve from SOLAR2.BAS
(2 X 2.046 cm Silicon Solar Cell)

analog converter connected to the ISAAC 2000 at channel 2 where the input range is set to +/- 100 mV. The thermocouple to analog converter is actually a thermocouple amplifier and provides 1 mV/°C output. For example: 28 mV would equal 28°C.

3. Solar Simulation

The Kratos light source used for solar simulation uses a xenon arc lamp. The Kratos uses a series of condensers and filters to remove undesired line spectra in its spectrum. The Kratos light source cannot be accurately calibrated until a bipolar power supply is used with the system. Solar simulator intensities are determined by I_{sc}. [Ref. 32] By using the bipolar power supply, a true I_{sc} can be generated.

When the Kratos light source was tested for the first time, the water filter experienced several leaks. After the leaks were fixed, the Kratos functioned normally. The uniform beam is only two inches in diameter when the Kratos is sitting on a lab bench. The distance from the lab bench surface to the Kratos 90° light tube assembly is fourteen inches. The Kratos should be elevated approximately three to five feet. This elevation should give a uniform beam with an area of one square foot.

The equipment to measure the actual spectrum of the Kratos is not available, but a standard solar cell can be purchased from the Jet Propulsion Laboratory in Pasadena,

California. This standard solar cell is calibrated on telemetered balloon flights and should be used every time the light source is used. This initial calibration of the light source will reduce the number of errors made by a improper setting for the light source. The standard cell should also be the last cell tested before the light source is shut down to ensure that the light source has not changed intensity.

B. GENERATING CURRENT-VOLTAGE CURVES

The primary means to evaluate a solar cell is by its current-voltage characteristics. These characteristics are usually measured at a stabilized temperature of 28°C and AM0.

The current-voltage curve is generated by varying the resistance in the load from zero to infinity.

One method to generate current-voltage curves is to use a variable resistive load. This method cannot yield a true I_{sc}. A schematic of this variable resistive load is given in Figure 4.2. This method was used to generate current-voltage curves since a bipolar power supply was not available. Various potentiometers were tried and none performed with the linear response needed to generate a smooth curve. At least 100 kohms was needed to reach a current near I_{sc}. This twenty-turn potentiometer was not linear near the I_{sc} point, and a very rapid transition from I_{sc} to V_{oc} occurred. A

bipolar power supply capable of sinking current should be used to generate current-voltage curves.

In summary, to test solar cells, the following should be observed:

1. Use a standard solar cell made from the same material as the test cell. This is done to calibrate the light source. Ensure the proper value of I_{mc} is generated before continuing.

2. Test the standard cell before beginning tests and after tests are completed to ensure the light source has not changed intensity.

3. The temperature should be set to 28° +/- 2°C.

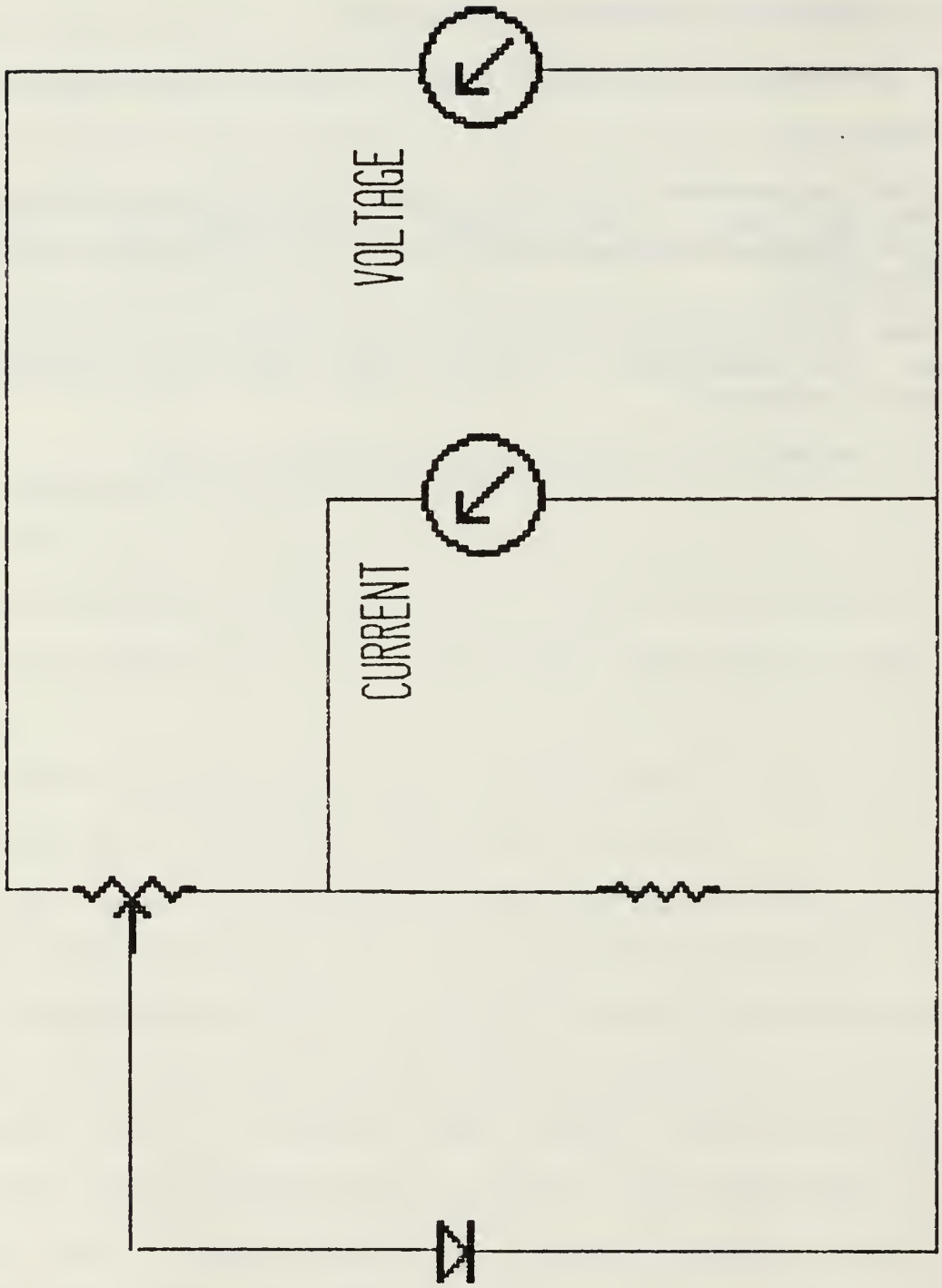

Figure 4.2 Schematic of Variable Load Resistor

V. ERROR ANALYSIS

A. SOURCES OF ERRORS

When any automated data acquisition system is constructed, errors will be generated in the data collection and conversion. These errors are usually not serious and can be compensated, if they are understood and the source is known.

1. Data Conversion

An error is generated when converting analog values to binary representation and then converting the binary number to a decimal representation. This error is given by:

$$\text{Max Error} = (\text{Input Range} / 2) * (1 / 2^n)$$

for example:

Input Range = +/- 5 Volts

Number of bits(n) = 12

$$(10 / 2) * (1 / 4096) = 1.2207 \times 10^{-3} \text{ Volts}$$

There are two methods to decrease this error. These methods are:

1) Decrease the input range

2) Increase the number of bits

The best method is to increase the number of bits, but the

most practical method is to decrease the input range.

for example:

Input Range = +/- 100 mV

Number of bits(n) = 12

$(.1 / 2) * (1 / 4096) = 1.2207 \times 10^{-5}$ volts

In summary, always use the smallest input range possible for your measurements.

2. Light Source

The light source will be the largest source of errors in any solar cell analysis. The spectral output of the xenon lamp will change with time. The optical quality of the mirrors and condensing system will also change with time. This is why the light source should be closely monitored and calibrated before any testing is done.

The solar simulator spectral response can be tested with narrow bandpass or cutoff filters used with spectral response detectors. [Ref. 33]

3. Current Measurement

The current should be measured across a precision resistor. This precision resistor should be calibrated by the Bureau of Standards. If a Bureau of Standards precision resistor is not used, the error can be excessive and qualitative results will not be obtained.

VI. CONCLUSIONS

The following projects need to be completed before the solar power laboratory is functional:

1. Integrate the Kepco bipolar power supply into the system.

2. Construct a platform to mount the Kratos light source on. This platform should be motor driven and have a zero-to-five foot range of motion.

3. Construct a electrical heating system for the solar cell test block to decrease the amount of time needed for temperature effect measurements.

4. Purchase a standard solar cell from JPL/NASA

5. Purchase a precision resistor from the National Bureau of Standards.

The following projects are optional and not necessary for the laboratory to become functional.

1. Construct a motor driven tilt table to mount the solar cell test block on. This tilt table will be used for angle of incidence measurements. The tilt table can be driven by the D/A card in the ISAAC 2000 and a analog joystick connected to the IBM PC/XT.

2. Expand the SOLAR.BAS program capabilities. The program should be able to write data collected from solar cells to a disk and then read that data back for analysis. The program can also be expanded to graph the results on the color monitor.

APPENDIX A

SOLAR.BAS LISTING

```
100 '  ************************************************************
110 '  *                                                          *
120 '  *               SOLAR CELL TESTING PROGRAM                 *
130 '  *                       version 1.0                        *
140 '  *                          by                              *
150 '  *                     KEVIN T. MABIE                       *
160 '  *                                                          *
170 '  *---------------------JUNE 21, 1985----------------------*
180 '  *                                                          *
190 '  * THIS PROGRAM WAS WRITTEN AS PART OF A THESIS IN THE      *
200 '  * SPACE OPERATIONS CURRICULUM AT THE NAVAL POSTGRADUATE    *
210 '  * SCHOOL. THIS PROGRAM USES A IBM PC/XT, A HP-7475A        *
220 '  * PLOTTER AND A ISAAC A/D CONVERTER.                       *
230 '  *                                                          *
240 '  ************************************************************
250 '
260 '
400       CLEAR
500       CLEAR   ,&HDE00 ,2000
510       IBINIT = &HDE00
520       BLOAD  "C:isaacomm.bin",IBINIT
530       CALL IBINIT(IBRD%,IBWRT%,IBCMD%,IBWAIT%,IBRPP%,IBONL%,
          IBRSC%,IBSIC%,IBSRE%,IBRTL%,IBRSV%,IBLPE%,IBPAD%,
          IBSAD%,IBIST%,IBDMA%,IBEOS%,IBTMO%,IBEOT%,IBGTS%,IBCAC%,
          IBDIAG%,IBSTA%,IBERR%,IBCNT%)
540       BD% = 0
550       CALL IBSIC%(BD%)
560       ONE% = 1
570       CALL IBSRE%(BD%,ONE%)
580       WRITESTRING% = &HDE03
590       READSTRING% = &HDE06
600       BREAK% = &HDE09
610       READNUM% = &HDE0C
620       BDUMP% = &HDE0F
630       BDUMPCS% = &HDE12
640       CONVERT% = &HDE15
650       V% = 200
660       CALL IBTMO%(BD%,V%)
670       OPEN "com1:9600,n,8,1,cs,ds,cd" AS #2
680       DIM BUF%(1023)
690       INUM%=17
700       '
710       '
900       ISC=0:VOC=0:PMAX=0:VMAX=0:IMAX=0:FF=0
910       EFFICIENCY=0:TEMPERATURE=0
1000      WIDTH 40
```

```
1010     COLOR 14,1,0
1020     CLS
1030     VOLTS$="FASC 32,0,0,1,5,1;LAST"
1040     CURRENT$="FASC 32,1,1,1,5,1;LAST"
1050     TEMPERATURE$="FASC 32,2,2,1,5,1;LAST"
1055     LOCATE 10,1
1060     INPUT "HOW MANY POINTS ON THE I-V CURVE ";N
1065     LOCATE 12,5
1070     INPUT "INPUT THE CELL ID# ";CELL$
1075     LOCATE 14,5
1080     INPUT "INPUT CELL WIDTH IN CM ";W
1085     LOCATE 16,5
1090     INPUT "INPUT CELL HEIGHT IN CM ";H
1095     CLS
1100     DIM X(N),Y(N)
1110     FOR J=1 TO N
1115       COLOR 14,1,0
1120       VOLTS=0:CURRENT=0
1130       FOR I= 1 TO 10
1140         CALL WRITESTRING%(INUM%,VOLTS$)
1150         CALL READNUM%(INUM%,STATUS%)
1155         IF STATUS%<>0 THEN BEEP:PRINT
             "---ICL SYNTAX ERROR---":END
1160         CALL READNUM%(INUM%,RAWVAL%)
1170         VOLTS = (RAWVAL%*10/4096-5) + VOLTS
1180       NEXT I
1190       LOCATE 8,5 :PRINT "VOLTAGE AT CHANNEL #1 = ";
1200       X(J)=VOLTS/10
1210       PRINT USING "##.####";VOLTS/10
1220       FOR K=1 TO 10
1230         CALL WRITESTRING%(INUM%,CURRENT$)
1240         CALL READNUM%(INUM%,STATUS%)
1245         IF STATUS%<>0 THEN BEEP:PRINT
             "---ICL SYNTAX ERROR---":END
1250         CALL READNUM%(INUM%,RAWVAL%)
1260         CURRENT =(RAWVAL%*.1/4096-.05)/.1 + CURRENT
1270       NEXT K
1280       LOCATE 10,5 :PRINT "CURRENT AT CHANNEL #2 = ";
1290       PRINT USING "###.###";(ABS(CURRENT)/10)*1000
1300       Y(J)=(ABS(CURRENT)/10)
1310       CALL WRITESTRING%(INUM%,TEMPERATURE$)
1320       CALL READNUM%(INUM%,STATUS%)
1325       IF STATUS%<>0 THEN BEEP:PRINT
           "---ICL SYNTAX ERROR---":END
1330       CALL READNUM%(INUM%,RAWVAL%)
1340       TEMPERATURE=(RAWVAL%*.1/4096-.05)*1000 +TEMPERATURE
1343       COLOR 4,1,0
1345       LOCATE 15,5:PRINT "TEMPERATURE = ";TEMPERATURE/J
1350     NEXT J
1360     TEMPERATURE=TEMPERATURE/N
1370   VOC=X(1):ISC=Y(1)
1380   FOR I=1 TO N-1
```

```
1390      IF VOC>=X(I+1) THEN 1410
1400      VOC=X(I+1)
1410    NEXT I
1420    FOR I=1 TO N-1
1430      IF ISC>=Y(I+1) THEN 1450
1440      ISC=Y(I+1)
1450    NEXT I
1460    PMAX=X(1)*Y(1)
1470    VMAX=X(1):IMAX=Y(1)
1480    FOR I=1 TO N-1
1490      IF PMAX>=X(I+1)*Y(I+1) THEN 1520
1500      PMAX=X(I+1)*Y(I+1)
1510      VMAX=X(I+1):IMAX=Y(I+1)
1520    NEXT I
1530    FF=PMAX/(ISC*VOC)
1540    EFFICIENCY=(ISC*VOC*FF)/(135.5*H*W)*100
1550    COLOR 14,1,0:LOCATE 20,1
1560    INPUT "WOULD YOU LIKE THE DATA PLOTTED(Y/N)";YESNO$
1570    IF (YESNO$="Y") OR (YESNO$="y") THEN GOSUB 9000
1580    CLS:LOCATE 12,1
1590    INPUT "WOULD YOU LIKE ANOTHER RUN (Y/N)";YESNO$
1600    IF (YESNO$="Y") OR (YESNO$="y") THEN 400
1610    SYSTEM
2000    '
2010    '
9000    CLS:LOCATE 12,1
9010    INPUT "PREPARE THE PLOTTER AND PRESS RETURN";A$
10000   OPEN "COM2:9600,S,7,1,RS,CS65535,DS,CD" AS #1
10010   PRINT #1,"IN;SP1;IP2000,1600,8400,6200;"
10020   PRINT #1,"SC0,1200,0,150;"
10030   PRINT #1,"PU0,0PD1200,0,1200,150,0,150,0,0PU"
10040   PRINT #1,"SI.2,.3;TL1.5,0"
10050   FOR X=0 TO 1200 STEP 100
10060     PRINT #1,"PA";X,",0;XT;"
10070     IF X<100 THEN PRINT #1,"CP-1.3,-1;LB";X;CHR$(3)
10075     IF X<1000 AND X>99 THEN PRINT #1,"CP-2.3,-1;LB";X;CHR$(3)
10077     IF X>999 THEN PRINT #1,"CP-2.8,-1;LB";X;CHR$(3)
10080   NEXT X
10090   FOR Y=0 TO 150 STEP 10
10100     PRINT #1,"PA 0,",Y,"YT;"
10110     IF Y<100 THEN PRINT #1,"CP-3,-.25;LB";Y;CHR$(3)
10120     IF Y>99 THEN PRINT #1,"CP-4,-.25;LB";Y;CHR$(3)
10130   NEXT Y
10140   PRINT #1,"SI.35,.5"
10150   PRINT #1,"PA450,0;CP-1,-1.8;LBVOLTAGE (MV)"+CHR$(3)
10160   PRINT #1,"PA0,45;DI0,1;CP-1,1.4;LBCURRENT (MA)"+CHR$(3)
10165   PRINT #1,"DI;PU"
10170   FOR I=1 TO N
10180     PRINT #1,"PA";INT(X(I)*1000);INT(Y(I)*1000);"PD"
10190   NEXT I
10200   PRINT #1,"SP2;SI.1,.2"
10210   PRINT #1,"PU;PA930,145;CP0,0;LBIsc  = ";ISC*1000;CHR$(3)
```

```
10220  PRINT #1,"CP;LBVoc  = ";VOC;CHR$(3)
10230  PRINT #1,"CP;LBPMAX = ";PMAX;CHR$(3)
10240  PRINT #1,"CP;LBVMAX = ";VMAX;CHR$(3)
10250  PRINT #1,"CP;LBIMAX = ";IMAX*1000;CHR$(3)
10260  PRINT #1,"CP;LBFF   = ";FF;CHR$(3)
10270  PRINT #1,"CP;LBEFF  = ";EFFICIENCY;CHR$(3)
10280  PRINT #1,"CP;LBTEMP = ";TEMPERATURE;CHR$(3)
10290  PRINT #1,"PU;PA1175,145;CP0,0;LBMA";CHR$(3)
10300  PRINT #1,"CP;LBV"+CHR$(3)
10310  PRINT #1,"CP;LBW"+CHR$(3)
10320  PRINT #1,"CP;LBV"+CHR$(3)
10330  PRINT #1,"CP;LBMA"+CHR$(3)
10340  PRINT #1,"CP;CP;LB%"+CHR$(3)
10350  PRINT #1,"CP;LBC"+CHR$(3)
10360  PRINT #1,"PU;PA720,145;CP0,0;LBDATE : ";DATE$;CHR$(3)
10370  PRINT #1,"CP;LBTIME : ";TIME$;CHR$(3)
10380  PRINT #1,"CP;LBID # : ";CELL$;CHR$(3)
10390  PRINT #1,"PA0,0;SP0;"
10400  RETURN
```

APPENDIX B

SOLAR2.BAS LISTING

```
100 '  ************************************************************
110 '  *                                                          *
120 '  *               SOLAR CELL TESTING PROGRAM                 *
130 '  *                version 1.1 (AUTOSCALING)                 *
140 '  *                          by                              *
150 '  *                     KEVIN T. MABIE                       *
160 '  *                                                          *
170 '  *---------------------JUNE 21, 1985----------------------*
180 '  *                                                          *
190 '  * THIS PROGRAM WAS WRITTEN AS PART OF A THESIS IN THE      *
200 '  * SPACE OPERATIONS CURRICULUM AT THE NAVAL POSTGRADUATE    *
210 '  * SCHOOL. THIS PROGRAM USES A IBM PC/XT, A HP-7475A        *
220 '  * PLOTTER AND A ISAAC A/D CONVERTER.                       *
230 '  *                                                          *
240 '  ************************************************************
250 '
260 '
400       CLEAR
500       CLEAR   ,&HDE00 ,2000
510       IBINIT = &HDE00
520       BLOAD  "C:isaacomm.bin",IBINIT
530       CALL IBINIT(IBRD%,IBWRT%,IBCMD%,IBWAIT%,IBRPP%,
          IBONL%,IBRSC%,IBSIC%,IBSRE%,IBRTL%,IBRSV%,IBLPE%,
          IBPAD%,IBSAD%,IBIST%,IBDMA%,IBEOS%,IBTMO%,IBEOT%,
          IBGTS%,IBCAC%,IBDIAG%,IBSTA%,IBERR%,IBCNT%)
540       BD% = 0
550       CALL IBSIC%(BD%)
560       ONE% = 1
570       CALL IBSRE%(BD%,ONE%)
580       WRITESTRING% = &HDE03
590       READSTRING% = &HDE06
600       BREAK% = &HDE09
610       READNUM% = &HDE0C
620       BDUMP% = &HDE0F
630       BDUMPCS% = &HDE12
640       CONVERT% = &HDE15
650       V% = 200
660       CALL IBTMO%(BD%,V%)
670       OPEN "com1:9600,n,8,1,cs,ds,cd" AS #2
680       DIM BUF%(1023)
690       INUM%=17
700       '
710       '
900       ISC=0:VOC=0:PMAX=0:VMAX=0:IMAX=0:FF=0
910       EFFICIENCY=0:TEMPERATURE=0
1000      WIDTH 40
```

```
1010     COLOR 14,1,0
1020     CLS
1030     VOLTS$="FASC 32,0,0,1,5,1;LAST"
1040     CURRENT$="FASC 32,1,1,1,5,1;LAST"
1050     TEMPERATURE$="FASC 32,2,2,1,5,1;LAST"
1055     LOCATE 10,1
1060     INPUT "HOW MANY POINTS ON THE I-V CURVE ";N
1065     LOCATE 12,5
1070     INPUT "INPUT THE CELL ID# ";CELL$
1075     LOCATE 14,5
1080     INPUT "INPUT CELL WIDTH IN CM ";W
1085     LOCATE 16,5
1090     INPUT "INPUT CELL HEIGHT IN CM ";H
1095     CLS
1100     DIM X(N),Y(N)
1110     FOR J=1 TO N
1115       COLOR 14,1,0
1120       VOLTS=0:CURRENT=0
1130       FOR I= 1 TO 10
1140         CALL WRITESTRING%(INUM%,VOLTS$)
1150         CALL READNUM%(INUM%,STATUS%)
1155         IF STATUS%<>0 THEN BEEP:PRINT
             "---ICL SYNTAX ERROR---":END
1160         CALL READNUM%(INUM%,RAWVAL%)
1170         VOLTS = (RAWVAL%*10/4096-5) + VOLTS
1180       NEXT I
1190       LOCATE 8,5 :PRINT "VOLTAGE AT CHANNEL #1 = ";
1200       X(J)=VOLTS/10
1210       PRINT USING "##.####";VOLTS/10
1220       FOR K=1 TO 10
1230         CALL WRITESTRING%(INUM%,CURRENT$)
1240         CALL READNUM%(INUM%,STATUS%)
1245         IF STATUS%<>0 THEN BEEP:PRINT
             "---ICL SYNTAX ERROR---":END
1250         CALL READNUM%(INUM%,RAWVAL%)
1260         CURRENT =(RAWVAL%*.1/4096-.05)/.1 + CURRENT
1270       NEXT K
1280       LOCATE 10,5 :PRINT "CURRENT AT CHANNEL #2 = ";
1290       PRINT USING "###.###";(ABS(CURRENT)/10)*1000
1300       Y(J)=(ABS(CURRENT)/10)
1310       CALL WRITESTRING%(INUM%,TEMPERATURE$)
1320       CALL READNUM%(INUM%,STATUS%)
1325       IF STATUS%<>0 THEN BEEP:PRINT
           "---ICL SYNTAX ERROR---":END
1330       CALL READNUM%(INUM%,RAWVAL%)
1340       TEMPERATURE=(RAWVAL%*.1/4096-.05)*1000 +TEMPERATURE
1343       COLOR 4,1,0
1345       LOCATE 15,5:PRINT "TEMPERATURE = ";TEMPERATURE/J
1350     NEXT J
1360     TEMPERATURE=TEMPERATURE/N
1370   VOC=X(1):ISC=Y(1)
1380   FOR I=1 TO N-1
```

```
1390      IF VOC>=X(I+1) THEN 1410
1400      VOC=X(I+1)
1410    NEXT I
1420    FOR I=1 TO N-1
1430      IF ISC>=Y(I+1) THEN 1450
1440      ISC=Y(I+1)
1450    NEXT I
1460    PMAX=X(1)*Y(1)
1470    VMAX=X(1):IMAX=Y(1)
1480    FOR I=1 TO N-1
1490      IF PMAX>=X(I+1)*Y(I+1) THEN 1520
1500      PMAX=X(I+1)*Y(I+1)
1510      VMAX=X(I+1):IMAX=Y(I+1)
1520    NEXT I
1530    FF=PMAX/(ISC*VOC)
1540    EFFICIENCY=(ISC*VOC*FF)/(135.5*H*W)*100
1550    COLOR 14,1,0:LOCATE 20,1
1560    INPUT "WOULD YOU LIKE THE DATA PLOTTED(Y/N)";YESNO$
1570    IF (YESNO$="Y") OR (YESNO$="y") THEN GOSUB 9000
1580    CLS:LOCATE 12,1
1590    INPUT "WOULD YOU LIKE ANOTHER RUN (Y/N)";YESNO$
1600    IF (YESNO$="Y") OR (YESNO$="y") THEN 400
1610    SYSTEM
2000    '
2010    '
9000    CLS:LOCATE 12,1
9010    INPUT "PREPARE THE PLOTTER AND PRESS RETURN";A$
9020    XHIGHSCALE=INT(VOC*1000+20)
9030    YHIGHSCALE=INT(ISC*1000+20)
9040    '
9050    '
10000   OPEN "COM2:9600,S,7,1,RS,CS65535,DS,CD" AS #1
10010   PRINT #1,"IN;SP1;IP2000,1600,8400,6200;"
10020   PRINT #1,"SC0";XHIGHSCALE,0,YHIGHSCALE;"
10030   PRINT #1,"PU0,0PD";XHIGHSCALE,0,XHIGHSCALE,
        YHIGHSCALE,0,YHIGHSCALE,0,0;"PU"
10040   PRINT #1,"SI.2,.3;TL1.5,0"
10050   FOR X=0 TO INT(VOC*1000+10) STEP 100
10060     PRINT #1,"PA";X,",0;XT;"
10070     IF X<100 THEN PRINT #1,"CP-1.3,-1;LB";X;CHR$(3)
10075     IF X<1000 AND X>99 THEN PRINT #1,"CP-2.3,-1;LB";X;CHR$(3)
10077     IF X>999 THEN PRINT #1,"CP-2.8,-1;LB";X;CHR$(3)
10080   NEXT X
10090   FOR Y=0 TO INT(ISC*1000+10) STEP 30
10100     PRINT #1,"PA 0,",Y,"YT;"
10110     IF Y<100 THEN PRINT #1,"CP-3,-.25;LB";Y;CHR$(3)
10120     IF Y>99 THEN PRINT #1,"CP-4,-.25;LB";Y;CHR$(3)
10130   NEXT Y
10140   PRINT #1,"SI.35,.5"
10145   POINTS0=INT(1000*VOC/3)
10150   PRINT #1,"PA";POINTS0,0;"CP-1,-1.8;LBVOLTAGE (MV)"+CHR$(3)
10155   POINTS1=INT(ISC*1000/3)
```

```
10160  PRINT #1,"PA0",POINTS1;"DI0,1;CP-1,1.4;
       LBCURRENT (MA)"+CHR$(3)
10165  PRINT #1,"DI;PU"
10170  FOR I=1 TO N
10180    PRINT #1,"PA";INT(X(I)*1000);INT(Y(I)*1000);"PD"
10190  NEXT I
10200  PRINT #1,"SP2;SI.1,.2"
10204  POINTS2=INT(ISC*1000/2)
10205  POINTS3=INT(VOC*1000/20)
10210  PRINT #1,"PU;PA";POINTS3,POINTS2;"CP0,0;
       LBIsc  = ";ISC*1000;CHR$(3)
10220  PRINT #1,"CP;LBVoc  = ";VOC;CHR$(3)
10230  PRINT #1,"CP;LBPMAX = ";PMAX;CHR$(3)
10240  PRINT #1,"CP;LBVMAX = ";VMAX;CHR$(3)
10250  PRINT #1,"CP;LBIMAX = ";IMAX*1000;CHR$(3)
10260  PRINT #1,"CP;LBFF   = ";FF;CHR$(3)
10270  PRINT #1,"CP;LBEFF  = ";EFFICIENCY;CHR$(3)
10280  PRINT #1,"CP;LBTEMP = ";TEMPERATURE;CHR$(3)
10290  PRINT #1,"CP;LBDATE : ";DATE$;CHR$(3)
10300  PRINT #1,"CP;LBTIME : ";TIME$;CHR$(3)
10310  PRINT #1,"CP;LBID # : ";CELL$;CHR$(3)
10320  POINTS4=INT(VOC*1000/3.5)
10330  PRINT #1,"PU;PA";POINTS4,POINTS2;"CP0,0;LBMA";CHR$(3)
10340  PRINT #1,"CP;LBV"+CHR$(3)
10350  PRINT #1,"CP;LBW"+CHR$(3)
10360  PRINT #1,"CP;LBV"+CHR$(3)
10370  PRINT #1,"CP;LBMA"+CHR$(3)
10380  PRINT #1,"CP;CP;LB%"+CHR$(3)
10390  PRINT #1,"CP;LBC"+CHR$(3)
10400  PRINT #1,"PA0,0;SP0;"
10410  RETURN
```

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